Competition between dust scattering albedo and 2175 Å bump for ultraviolet colours of nearby disc galaxies

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Abstract

Observed ultraviolet (UV) colours of nearby disc galaxies show a reddening relative to their expected intrinsic colours. Since the 2175 Å bump found in the Milky Way's dust extinction law blues the UV colours, it might suggest that dust in nearby disc galaxies does not have the bump and that the Milky Way is exceptional. However, this conclusion can be modified by the effect of scatterings. If the scattering albedo decreases towards shorter wavelengths, observable UV colours redden. An extensive comparison between observed UV colours and those expected from radiative transfer simulations shows two types of dust suitable for nearby disc galaxies: (1) dust with a bump and a smaller albedo for a shorter wavelength (except for the bump range), and (2) dust without any bump but with an almost constant albedo. If very small carbonaceous grains responsible for the common unidentified infrared emission band are also the bump carrier, the former dust is favorable.

1 Introduction

Nearby starburst galaxies observed with the *IUE* satellite show a tight correlation between the observed ultraviolet (UV) spectral slope (β; $f_\lambda \propto \lambda^{-\beta}$) and the infrared (IR)-to-UV flux ratio (so-called IRX): a redder β for a larger IRX (Calzetti et al. 1994, Meurer et al. 1999). Witt & Gordon (2000) argued that the UV colour cannot be redden by the extinction law of the Milky Way (MW) because the strong absorption bump lies in the near-UV (NUV). Indeed, the extinction in the NUV is slightly larger than that in the far-UV (FUV) for the MW extinction law. Their finding may suggest the lack of the bump carrier in the interstellar medium (ISM) of the starburst galaxies.

Quiescent or modest star-forming "normal" galaxies show systematically redder UV colours than those of the *IUE* starburst galaxies (Bell 2002, Kong et al. 2004). This fact has recently been confirmed by the *GALEX* satellite for larger samples of nearby galaxies selected in the NUV or optical (Buat et al. 2005, Seibert et al. 2005). According to Witt & Gordon (2000), the MW type dust cannot reproduce even the UV colour of the *IUE* starburst galaxies, much less the redder UV colour of normal galaxies. Does the red UV colour of normal galaxies indicate the lack of the bump carrier in their ISM and distinguish the MW from these galaxies?

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On the other hand, Granato et al. (2000) pointed out that, even if the bump exists in the extinction law, the strength of the bump can be greatly reduced in the *attenuation law*, which is based on the ratio of the fluxes escaped from the medium to the intrinsic ones, by a radiative transfer effect coupled with an *age-selective obscuration*, i.e. young stars are more obscured selectively. More recently, Panuzzo et al. (2006) very well reproduced the red UV colours of the *GALEX* galaxies with the MW type dust. They adopted a realistic stellar distribution; younger stars are more deeply embedded in the dust disc, whereas older stars distribute more extensively (e.g., Robin et al. 2003). This realistic configuration of dust and stars depending on the stellar age produces an *age-selective obscuration*. This results in a *steep* attenuation law which overcomes the *blueing* by the bump.

In addition to the *age-selective obscuration*, Inoue et al. (2006) newly discussed the effect of the wavelength dependence of the scattering albedo on the UV colour. In fact, the dust properties adopted by Witt & Gordon (2000) and Granato et al. (2000, and also Panuzzo et al. 2006) are different from each other, especially the wavelength dependence of albedos. This point significantly affects the expected UV colour.

Inoue et al. (2006) thoroughly examined dust properties in nearby galaxies, in particular the presence of the bump and the wavelength dependence of the albedo, based on the *GALEX* colour. They adopted a one-dimensional plane-parallel radiative transfer model developed by Inoue (2005). While its computational geometry is one-dimensional, it can treat the clumpiness of stars and dust thanks to the mega-grain approximation (Városi & Dwek 1999). Owing to the computational cheapness of the one-dimensional calculation, they could investigate a very wide range of physical quantities of disc galaxies. After an extensive comparison between the *GALEX* data and their radiative transfer simulations, they found two types of dust suitable for the nearby disc galaxies: (1) dust with a bump and a smaller albedo for a shorter wavelength (except for the bump range), and (2) dust without any bump but with an almost constant albedo.

This paper is a digest of Inoue et al. (2006). If the readers need more details, they can be found in the original paper. The next section gives a brief summary of the radiative transfer model adopted in Inoue et al. (2006). A comparison of the *GALEX* data with the radiative transfer simulations is presented in section 3. The last section gives a discussion about the bump carrier.

2   Radiative transfer model

Inoue et al. (2006) examined several set-ups of the star–dust configuration in order to discuss its effect. Here we concentrate on their standard case, the most realistic one.

A clumpy ISM is produced by a two-phase ISM model based on Wolfire et al. (2003); the cold and warm neutral media are regarded as clumps and the inter-clump medium, respectively. As introduced by Inoue (2005), we can set the density contrast between these media and the clump filling factor by giving the ISM mean pressure and density. The clump size is given by its Jeans length. The gas and dust are confined in a disc with a vertical height, and clumps distribute randomly in the disc. Any systematic radial and vertical structures are not considered. The ranges of physical quantities considered are the ISM mean pressure as $10^{3.0-4.0}$ K cm^{-3}, the ISM mean density of hydrogen atom as

0.5–24 cm^{-3}, the half height of the dusty disc as 50–300 pc, and the dust-to-gas mass ratio as 0.001–0.01. These ranges well cover the values observed in nearby "normal" galaxies.

The stars are divided into three populations depending on the age: young (age $\leq$ 10 Myr), intermediate (10 Myr $<$ age $\leq$ 300 Myr), and old stars (age $>$ 300 Myr). The young stars are embedded in the clumps; the emissivity of these stars is reduced by a local obscuration factor. This is motivated by the fact that stars are formed in molecular clouds (i.e. clumps). The intermediate/old stars distribute with a smaller/larger scale-height than the dusty disc height. This is based on the observed age-dependent stellar distribution (e.g., Robin et al. 2003). This age-dependent distribution produces an age-dependent obscuration. Finally, an exponentially decaying star formation history with 5 Gyr e-folding time and the galactic age of 10 Gyr are assumed in order to obtain the luminosity fractions of the three stellar populations which are used as their weights in the composite process of the transmission rates of lights from these three populations (see equation [1] in Inoue et al. 2006).

Six dust models are compiled from the literature: two from Witt & Gordon (2000) (hereafter WG dusts) and four from Draine and co-workers (hereafter Draine dusts). Table 1 is a summary of the dust models. Witt & Gordon (2000) empirically derived the dust properties from a large compilation of astronomical observations. On the other hand, Draine and co-workers made theoretical models based on experimental optical constants of candidate materials for the interstellar dust. Note that Draine dusts are sometimes designed to fit astronomical observations by modifying the optical constants. Four types of dust compositions are considered: the MW, the SMC, the LMC av, and LMC 2. The LMC av type is an average dust composition over many sight lines towards the LMC, except for the supershell around the 30 Doradus, and the LMC 2 type is that towards the supershell.

Fig. 1 shows the extinction cross sections (panel [a]) and the albedos (panel [b]) of these models as a function of the wavelength. The extinction cross sections (i.e. extinction laws) are very similar between the WG dust and the Draine dust if we compare the same composition type. We find a prominent bump at 0.22 μm ($1/\lambda = 4.6$ μm^{-1}) in the MW and the LMC av types, a weak bump in the LMC 2 type, and no bump in the SMC type. On the other hand, the albedos are very different between the WG dust and the Draine dust (panel [b]). Except for the bump region, albedos of the WG dust (solid and dashed lines) show a flat wavelength dependence in $2\,\mu$m$^{-1} < 1/\lambda < 8\,\mu$m^{-1}, whereas those of the Draine dust (other lines) show a rapid decrease towards shorter wavelengths. Since the albedos estimated from observations show a large dispersion (Gordon 2004, see also Fig. 2 in Inoue et al. 2006), both dust models are still compatible with the data.

The radiative transfer equations are solved in a one-dimensional plane-parallel disc geometry. The disc consists of a clumpy dusty disc and three stellar discs described above. The clumpiness of the medium (i.e. the dust distribution) is treated by the mega-grain approximation developed by Városi & Dwek (1999). In this approximation, a dusty clump is regarded as a huge particle producing absorption and scattering effects like a normal single dust grain. Városi & Dwek (1999) clearly show the validity of the approximation by comparisons between the approximate solutions and their three-dimensional Monte Carlo radiative transfer solutions. A set of the practical equations are presented in Inoue (2005).

Table 1: Dust models.

Model	Reference	$k_{\mathrm{d},V}$ [a]
MW (WG)	Witt & Gordon (2000)	2.60×10^4
SMC (WG)	Witt & Gordon (2000)	1.56×10^4
MW (D)	Draine (2003)	2.60×10^4
SMC (D)	Weingartner & Draine (2001)	1.56×10^4
LMC av (D)	Weingartner & Draine (2001)	1.95×10^4
LMC 2 (D)	Weingartner & Draine (2001)	1.89×10^4

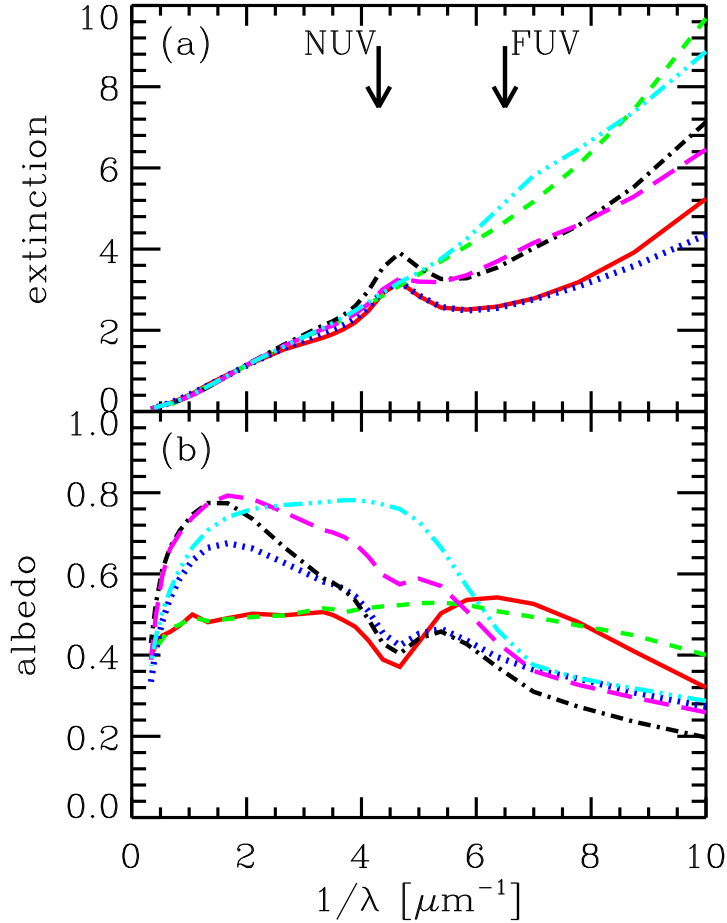[a] Visual extinction cross section per unit dust mass ($\mathrm{cm^2\ g^{-1}}$).

Figure 1: Differences of dust models. The panel (a) shows the extinction laws (extinction cross sections normalized by that at the V band) and the panel (b) shows the albedos. The solid and short-dashed lines are the MW and the SMC types of Witt & Gordon (2000), respectively. The dotted, dot-dashed, long-dashed, and three-dots-dashed lines are the MW, the LMC av, the LMC 2, and the SMC types of Draine (2003) and Weingartner & Draine (2001), respectively. The two downward arrows in the panel (a) show the effective wavelengths of the two $GALEX$ filters.

3 IR-to-UV flux ratio and *GALEX* colour

Since the *GALEX* colour is very sensitive to the presence of the bump and the wavelength dependence of the albedo, we may assess the dust models by comparing the observed *GALEX* colours with those expected from the radiative transfer simulations.

Fig. 2 shows the diagram of the IRX (dust IR-to-UV flux ratio, $F_{\rm dust}/F_{FUV}$) and the *GALEX* colour, $FUV - NUV$. The crosses and diamonds are the observed data of the nearby galaxies selected by NUV and FIR, respectively, taken from Buat et al. (2005). The solid and dashed lines are the loci expected from the extinction law and the Calzetti law (Calzetti 2001), respectively. The *GALEX* colours predicted by the radiative transfer simulations are divided into several bins in the IRX. The vertical error-bars show the bin widths. The filled circles and horizontal error-bars indicate the median location and the full width of the distribution of the colours in each bin. Six dust models are shown in each own panel from (a)–(f) as indicated in the panels.

The SMC (WG) case (panel [b]) shows a very good agreement with the data of the UV selected galaxies and the FIR selected galaxies with $F_{\rm dust}/F_{FUV} \lesssim 100$. The LMC av (D) and the LMC 2 (D) cases (panels [e] and [f]) are also compatible with the data. The colours predicted by the MW (D) case (panel [c]) are still ∼ 0.2–0.3 mag bluer than the observed ones because of a strong bump and a shallow UV slope in the extinction law, although a different IMF like a Kroupa IMF could reduce the discrepancy (Panuzzo et al. 2006). On the other hand, the predicted colours of the MW (WG) case (panel [a]) are largely separated from the observed data, say ∼ 0.5 mag at $F_{\rm dust}/F_{FUV} \sim 10$. For the SMC (D) case (panel [d]), the predicted colours are too red (∼ 0.5 mag at $F_{\rm dust}/F_{FUV} \sim 10$) because of a rapid decrease of the albedo between the two *GALEX* bands as shown in Fig. 1 (b).

There is no model which reproduces the FIR selected galaxies with $F_{\rm dust}/F_{FUV} \gtrsim 100$. For an opaque disc, we expect to have an attenuation law (i.e. transmission rate curve) independent of dust properties. Indeed, we find that the locations of the most opaque point in each panel are very similar; all dust models predict a very similar position on the diagram for $F_{\rm dust}/F_{FUV} \gtrsim 100$. However, the real galaxies show a very large dispersion in the region. Burgarella et al. (2005a) suggested that an effect of "decoupling" is important for such galaxies; stellar populations producing the UV and the IR are completely different. For example, the UV radiation comes from the population outside the obscured region, whereas the population heating dust which emits the IR radiation is embedded there. In this case, the UV colour is decoupled with the UV attenuation traced by $F_{\rm dust}/F_{FUV}$. In the framework of Inoue et al. (2006), such a "decoupling" would take place if we consider an intermittent SFH. Now, we have three stellar populations: young and intermediate ones embedded in clumps and in the dusty disc, and old one distributed diffusely to the outside of the disc. Under an intermittent SFH with a time-scale longer than ∼ 300 Myr (age threshold between the intermediate and old populations), we can expect that the luminosity weights strongly vary along the time, and then, the position of the most opaque case on the IRX–UV colour diagram would vary.

In summary, there are two sorts of dust suitable for the *GALEX* colours of nearby "normal" galaxies: (1) dust with a bump and a smaller albedo for a shorter wavelength like the Draine's MW, LMC av, and LMC 2 models, and (2) dust without any bump but an almost constant albedo like the WG's SMC model. Neither dust with a bump and a
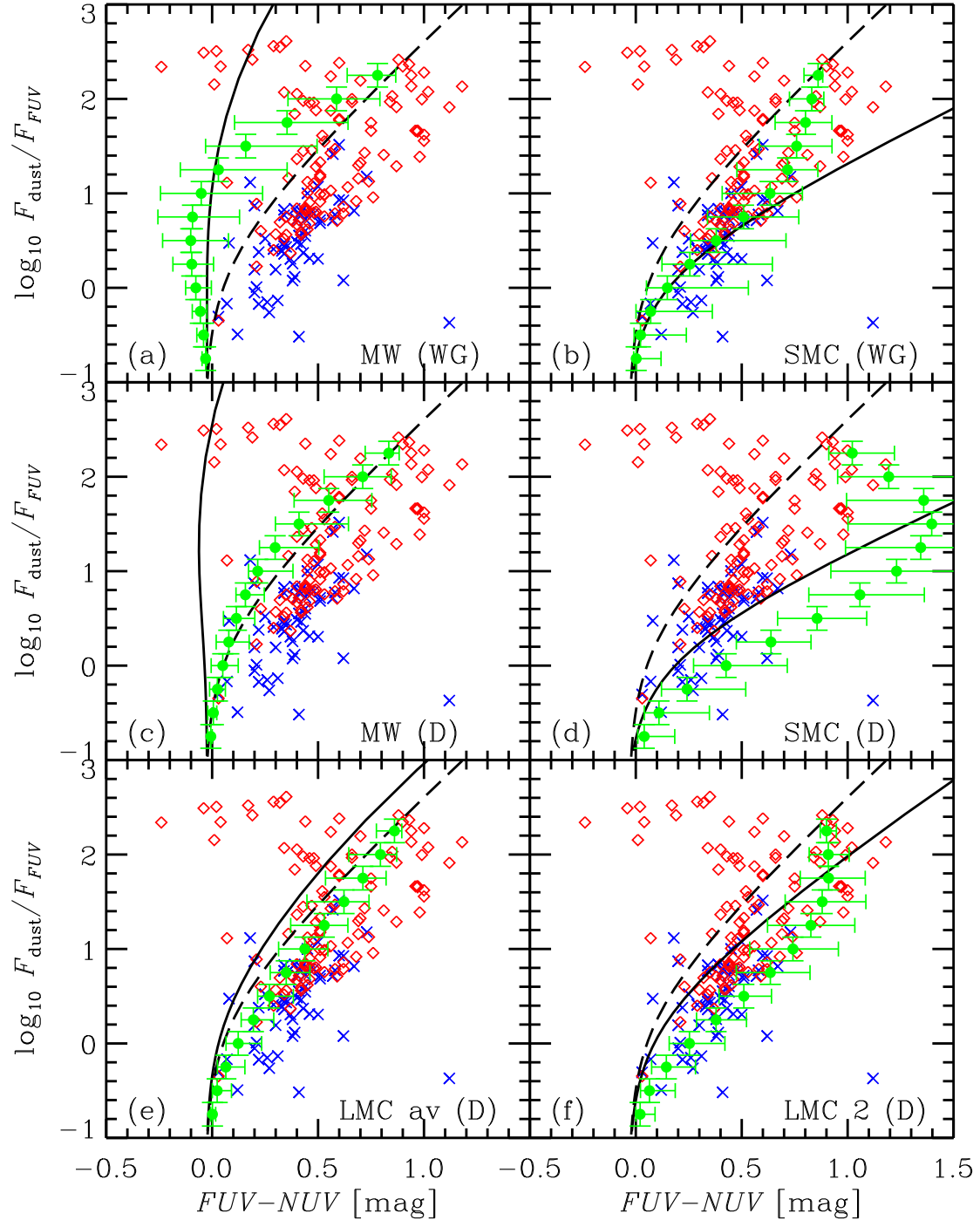
Figure 2: Dust IR-to-FUV flux ratio and the *GALEX* colour. The crosses and diamonds are observed data of the NUV selected and the FIR selected nearby galaxies, respectively, taken from Buat et al. (2005). The solid and dashed lines correspond to the extinction law and the Calzetti law, respectively. The colours predicted from the radiative transfer model are divided into several bins in the flux ratio. The vertical error-bars are the bin width, the horizontal error-bars are the full width of the distribution of $FUV - NUV$ in each bin, and the filled circles show the median location of the distribution.

constant albedo (except for the bump range) like the WG's MW model, nor dust without any bump and a smaller albedo for a shorter wavelength like the Draine's SMC model are suitable for the nearby galaxies observed with the *GALEX*. This competitive relation between the albedo and the bump should be robust if we change the adopted dust models.

4   Discussion

We have found two types of dust suitable for the nearby galaxies: one has a bump, the other does not have any bump. Here we discuss which type is more favorable from a viewpoint of the bump carrier search.

A suggested candidate of the bump carrier is very small carbonaceous grains like PAHs (Polycyclic Aromatic Hydrocarbons; Léger et al. 1989), QCCs (Quenched Carbonaceous Composites; Sakata et al. 1983), and UV processed HACs (Hydrogenerated Amorphous Carbon grains; Mennella et al. 1998), although this is not settled yet (Henning et al. 2004). These very small carbonaceous particles are confidently attributed to the unidentified infrared (UIR) emission band in 3–13 μm (Léger & Puget 1984, Sakata et al. 1984). The UIR emission band is quite common in the ISM of the MW (e.g., Onaka 2004) and of other galaxies (e.g., Genzel & Cesarsky 2000), except for low-metallicity ($\lesssim 1/5$ $Z/Z_{\odot}$) galaxies in which the UIR emission is weak or absent (Engelbracht et al. 2005). If the very small carbonaceous grains producing the UIR emission are really responsible for the bump, we should find the bump in other galaxies (but not so low-metallicity). Indeed, the bump found in M31 (Bianchi et al. 1996) and some distant galaxies, for example, a lensing galaxy at $z = 0.83$ (Motta et al. 2002) and Mg II absorption systems at $z = 1.5$ (Wang et al. 2004). There are also signs of the bump imprinted in the observed UV spectra of a galaxy at $z = 0.048$ (Burgarella et al. 2005b), of some *IUE* starburst galaxies (Noll & Pierini 2005), and of some star-forming galaxies at $z \sim 2$ (Noll & Pierini 2005). Therefore, dust with a bump is more favorable if the UIR carrier and the bump carrier are the same, the very small carbonaceous grains. For a firm conclusion, however, we would need more investigations.

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